Substrates of Ternary and Quaternary III-V Compounds

Partha S. Dutta

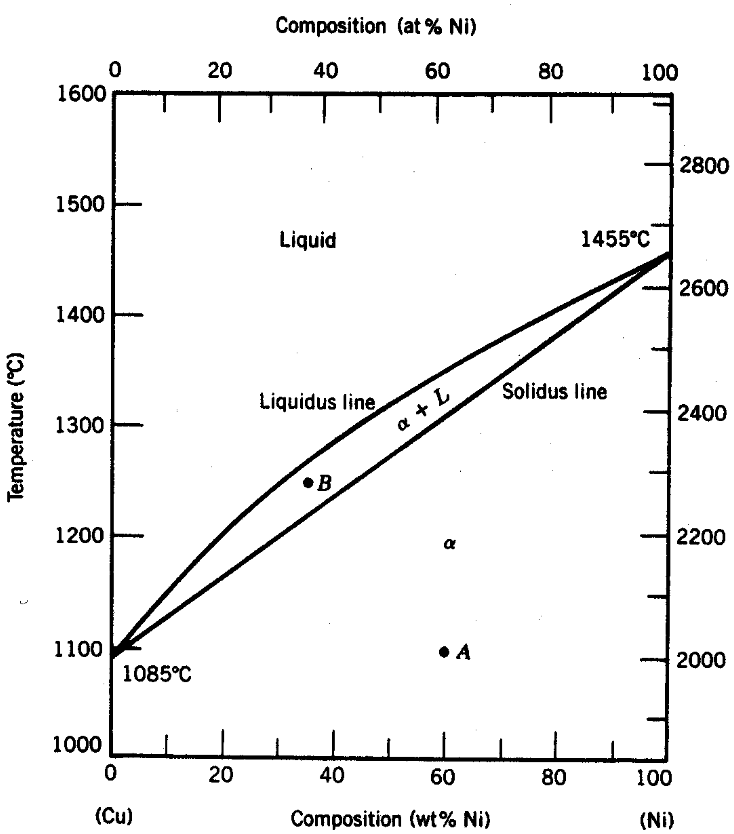
Electrical, Computer and Systems Engineering Department
&
Center for Integrated Electronics, Electronics Manufacturing and Electronic Media
Rensselaer Polytechnic Institute, Troy, NY

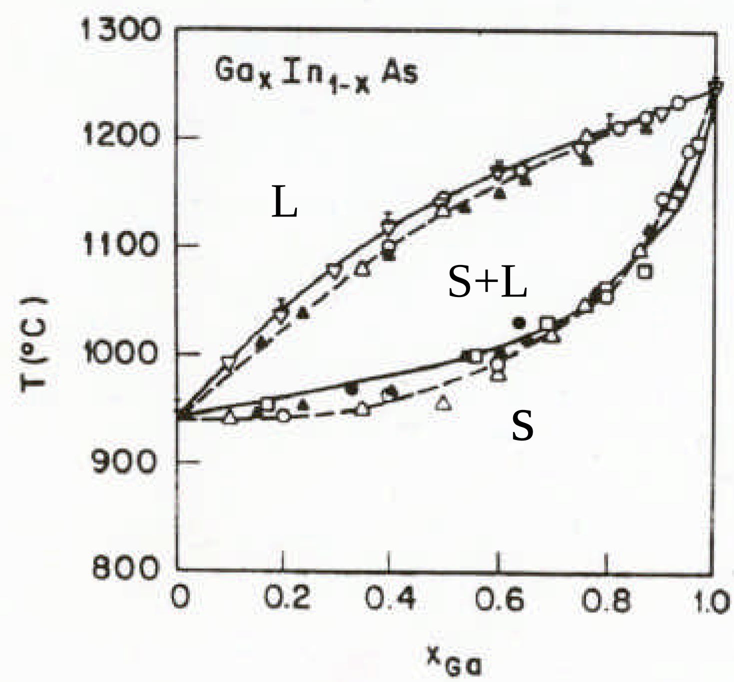
E-mail: duttap@rpi.edu

Outline

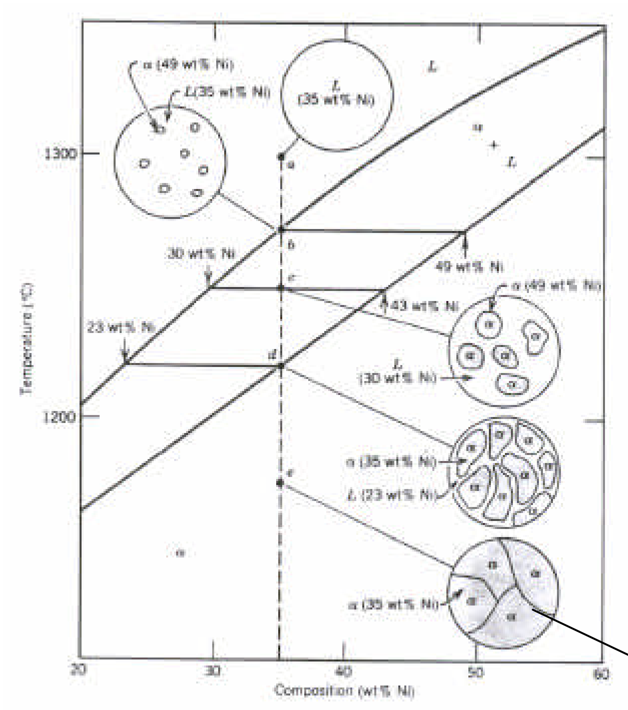
- The Science of Ternary Crystal Growth
  - The Metallurgical Aspect
  - Heat and Mass Transport
  - Ternary Seed Generation Methods
  - Alloy Composition Control (for homogeneous growth)
  - Temperature Stability Requirement
  - III-V Ternary Substrates
- Quaternary "Cooking"
- Alloy Bonding and Engineered Substrates
- Surface Preparation and Analysis of Antimonides

The Metallurgical Aspects of Ternary Alloy



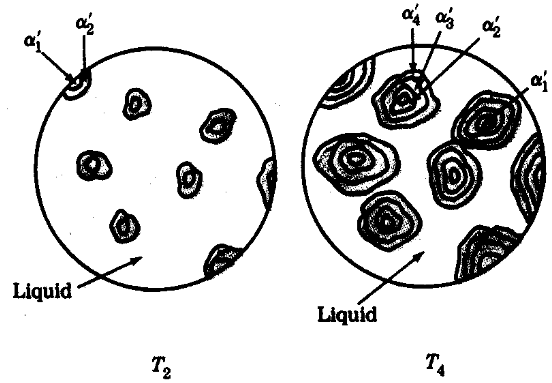


Compositional Variation and Crack Formation

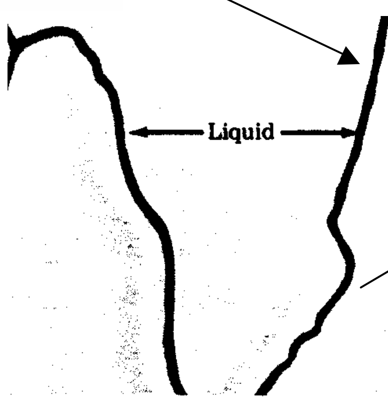


Cu-Ni

Microstructure of equilibrium grown solid



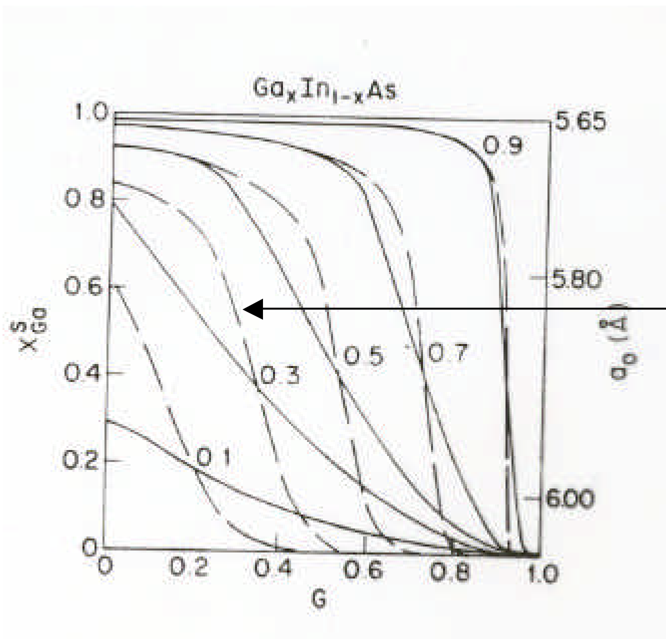
Microstructure of Non-Equilibrium grown solid

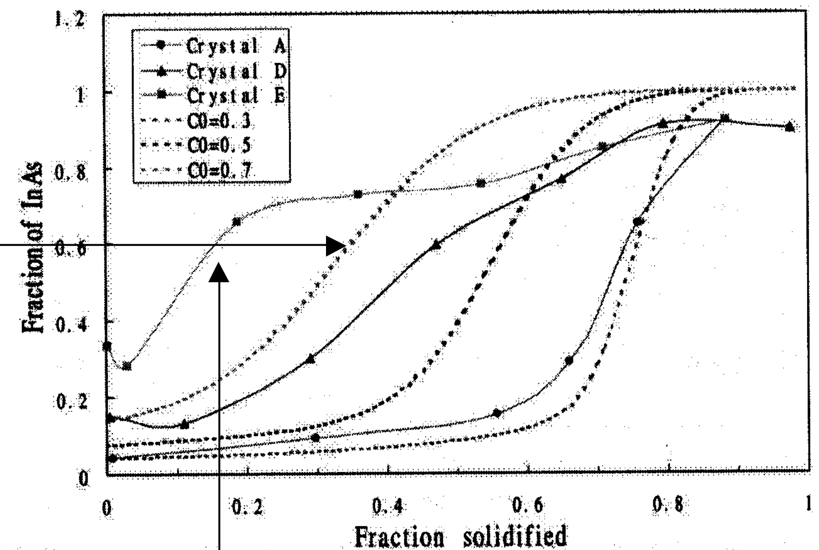


Cracks

GaInSb

Mass (Solute) Transport Mechanisms from Bulk Melt to Solid-Liquid (Growth) Interface





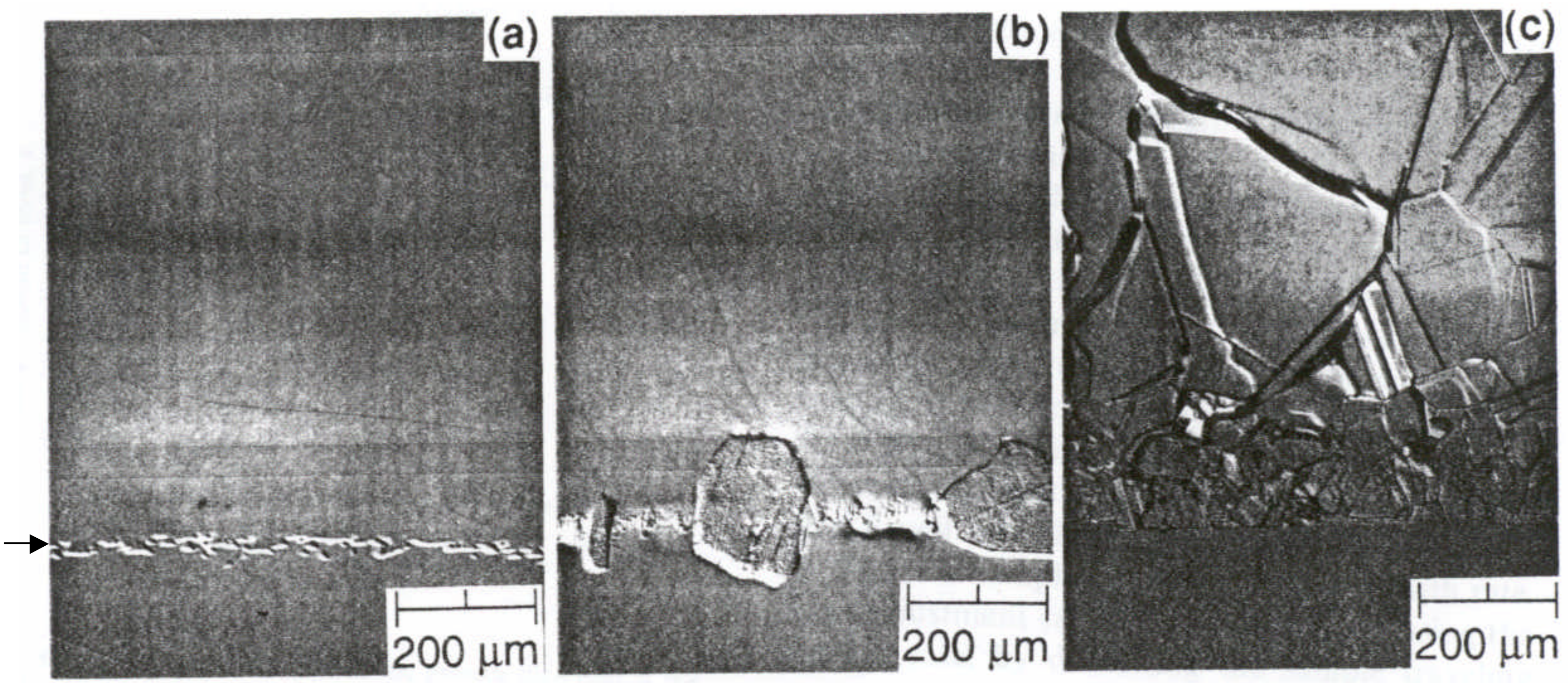
Convective Melt
(Full Mixing)

Effect of Solute Density

J. Crystal Growth **210**, 471 (2000)

Defects at the Seeding Interface

Seeding Interface

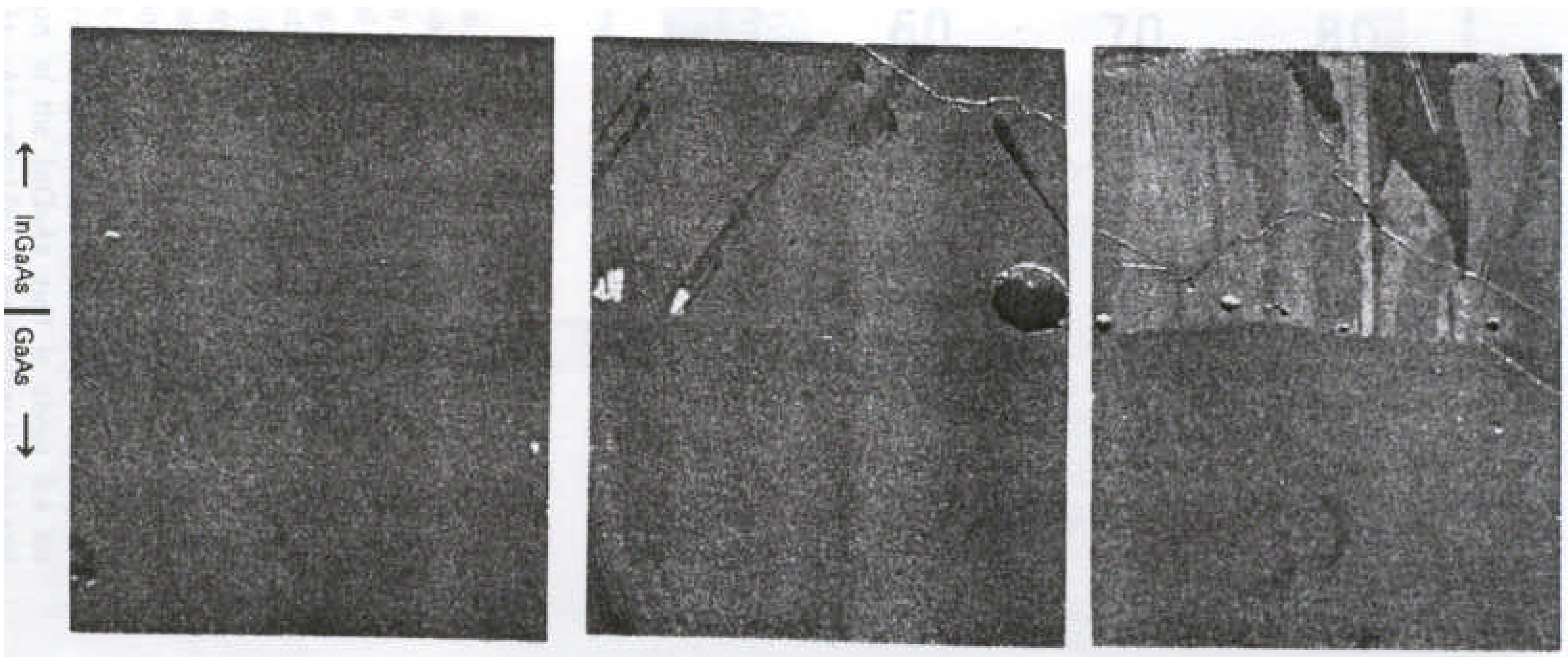


Δx= 5 mol% Δx= 10 mol% Δx= 15 mol%

- Maximum lattice mismatch ($\Delta a/a$) allowed for stable single crystal growth across step graded interface must be less than 0.5%

J. Crystal Growth **208**, 165 (2000)

Defects at the Seeding Interface

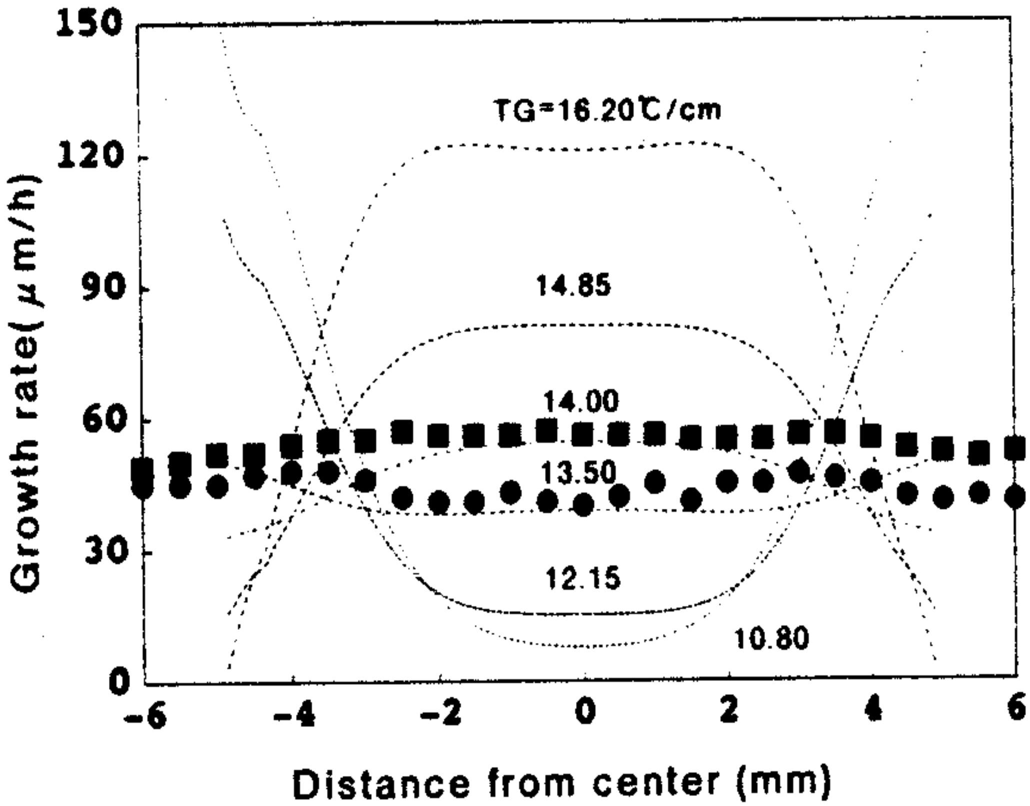


Δx= 5 mol% Δx= 7 mol% Δx= 12 mol%

- Maximum step composition change allowed for stable single crystal growth across interface must be less than 5 mol% (with lattice-mismatched end binaries)

J. Crystal Growth **197,** 769 (1999)

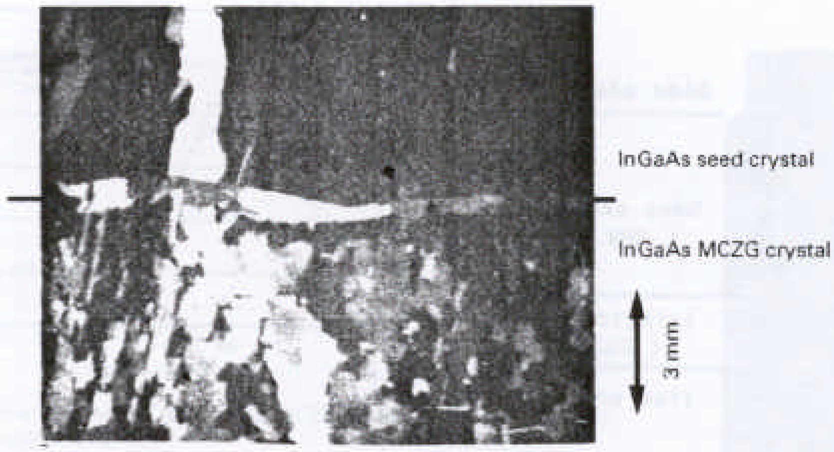
Effect of Temperature Gradient on Growth Rate



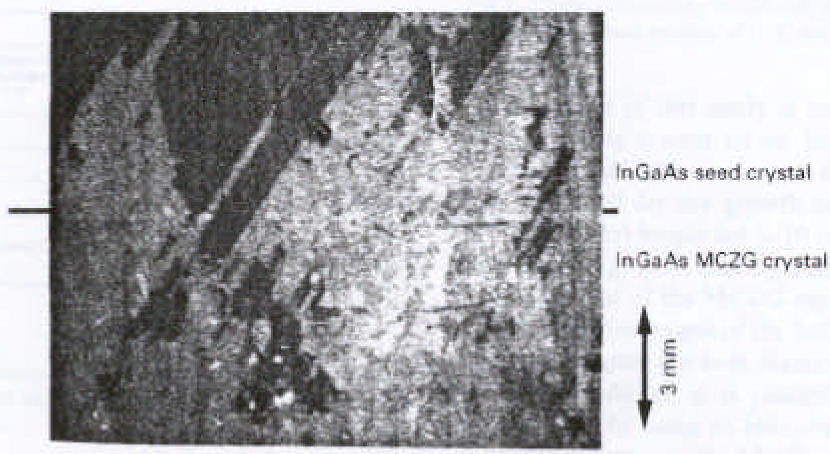
Growth Rate Increases with Temperature Gradient

J. Crystal Growth **166**, 463 (1996)

Effect of Temperature Gradient on Growth Morphology (with Solute Feeding)



(a) no GaAs supply rate is reduced

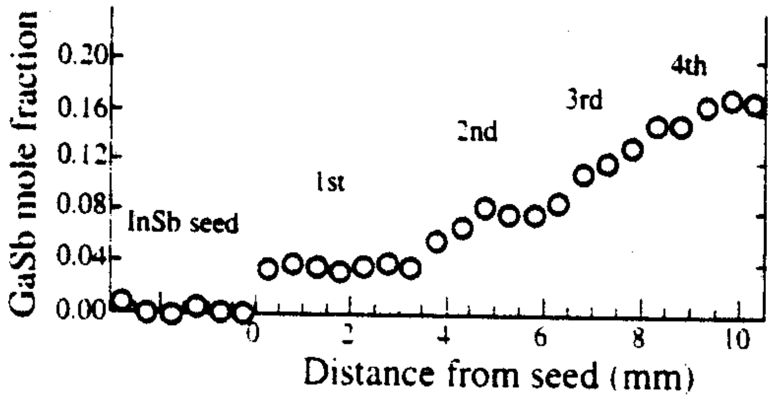


(b) the GaAs supply rate is reduced

Uncontrolled Solute transport leads to multiphase formation

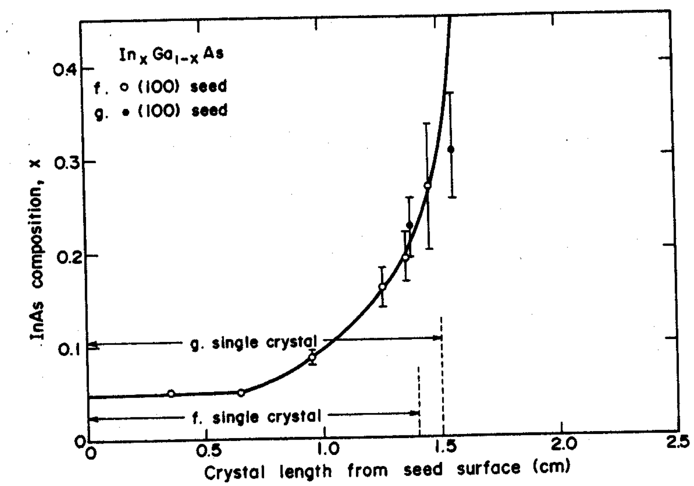
J. Crystal Growth **208**, 171 (2000)

Ternary Seed Generation

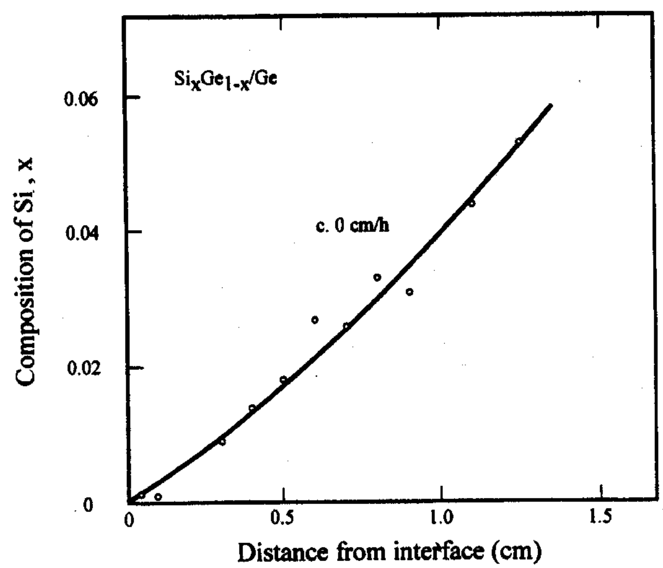


J. Crystal Growth **209**, 625 (2000)

- Bootstrapping
- Graded Composition Growth
- Diffusion Control Growth

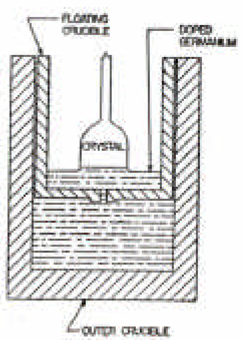


J. Crystal Growth **173**, 42 (1997)

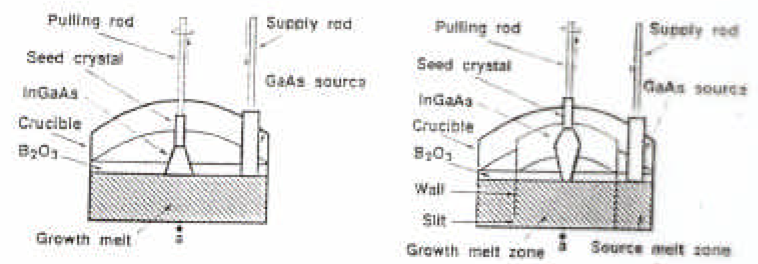


J. Crystal Growth **205**, 270 (1999)

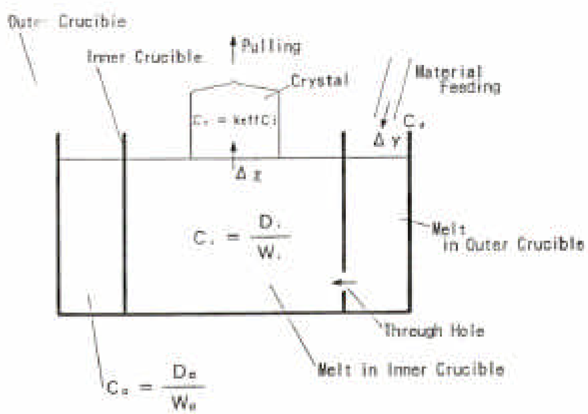
Alloy Composition Control by External Solute Feeding

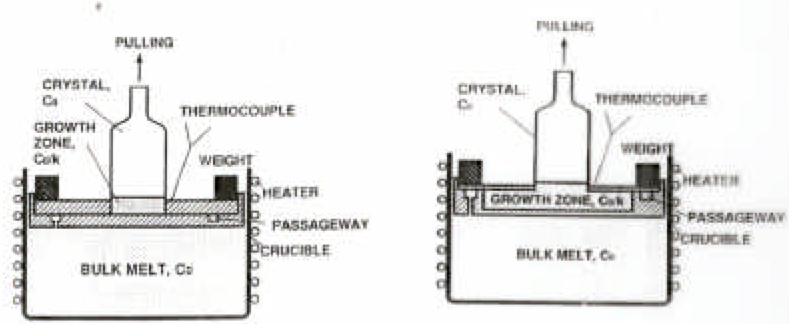


W.F. Leverton, J. Appl. Phys. **29**, 1241 (1958)



T. Kusunoki, Inst. Phys. Conf. Ser., **129**, 37 (1992)

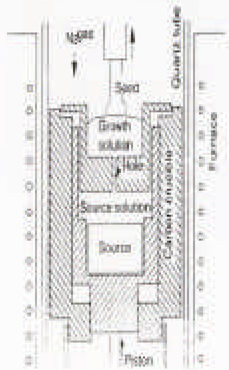




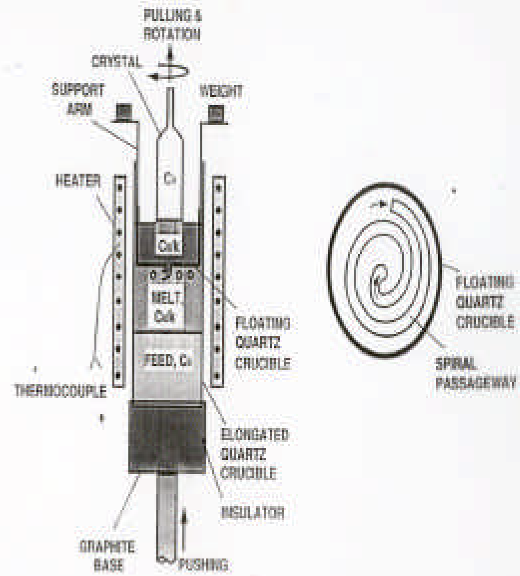
M.H. Lin & S. Kou, J. Crystal Growth **132**, 461 (1993)

Depleted components are fed during growth from an external source

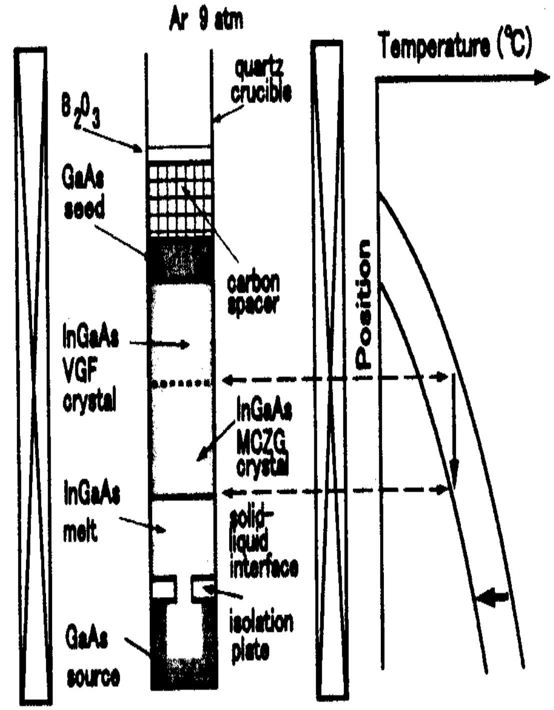
Alloy Composition Control by Optimizing Hole Diameter in Double Crucible Method



A. Tanaka et al. J. Crystal Growth **135**, 269 (1994)



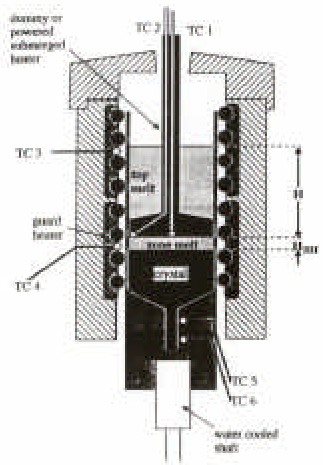
M.H. Lin & S. Kou, J. Crystal Growth **132**, 461 (1993)



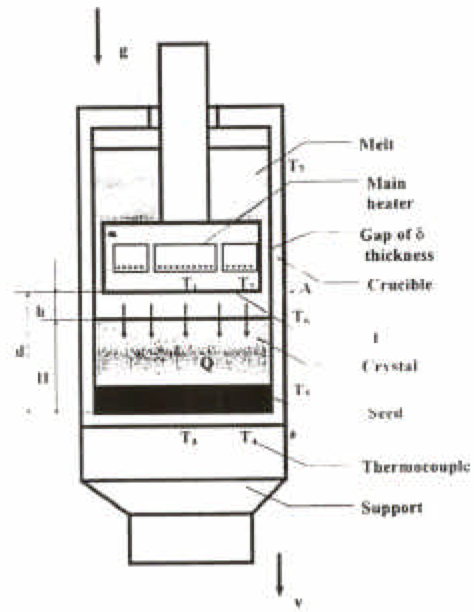
J. Crystal Growth **208**, 171 (2000)

Solute Transport from feed to seed is reduced by decreasing hole diameter

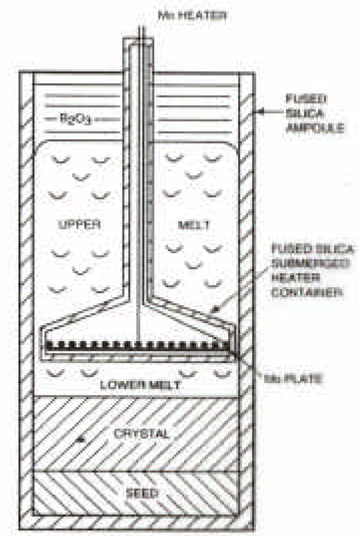
Alloy Composition Control via Submerged Baffle



A.G. Ostrogorsky, J. Crystal Growth **104**, 233 (1990)

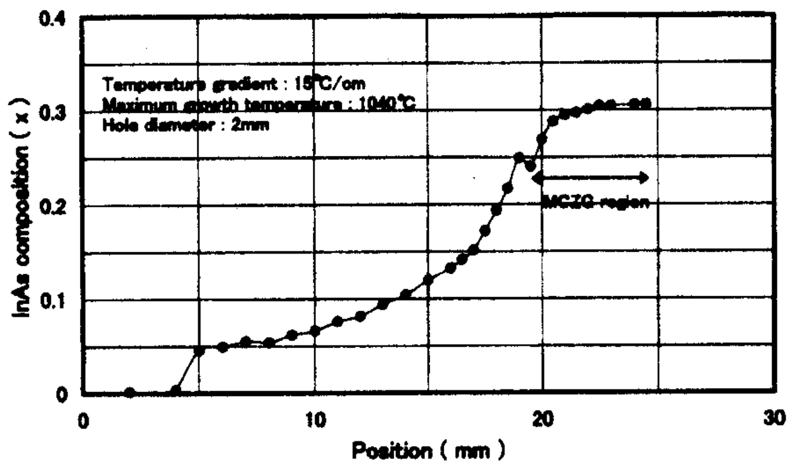


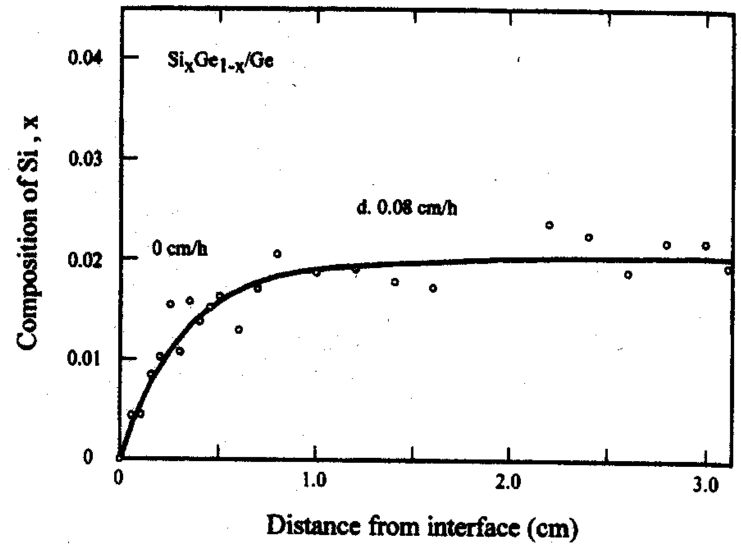
V.D. Golyshev, M.A. Gonik, Russian Patent N 1800854, (1990)

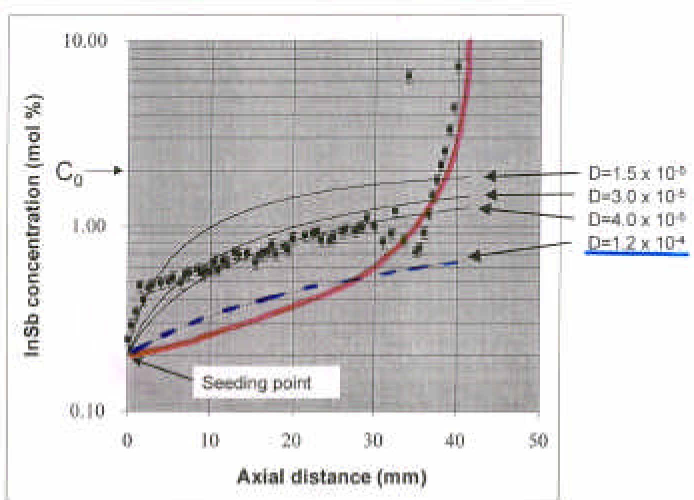


G.W. Iseler, Solid State Research, Lincoln Lab., MIT, 3, 9 (1994)

In-situ Alloy Composition Control by Varying Temperature Gradient and Growth Rate



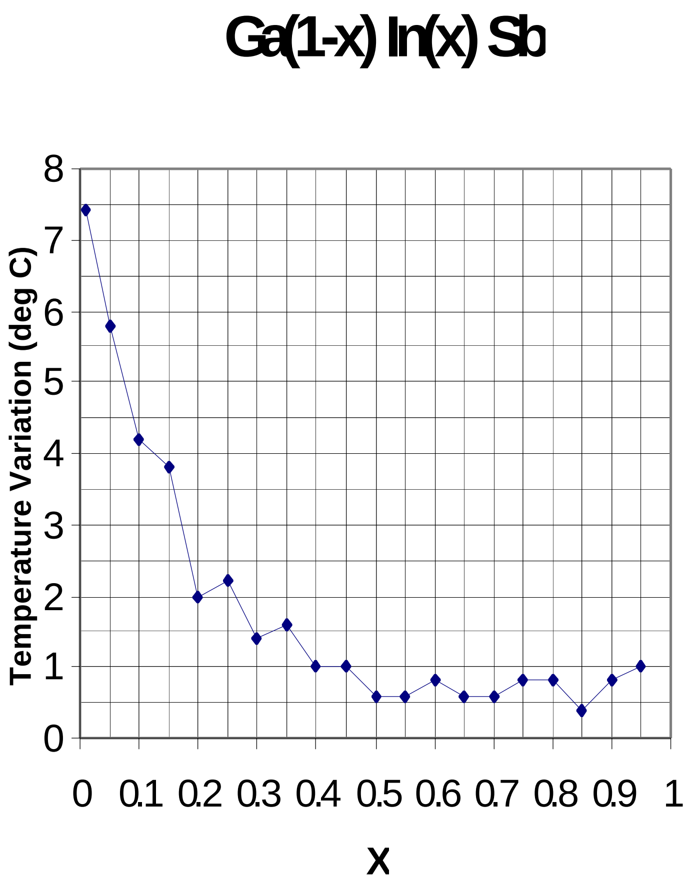


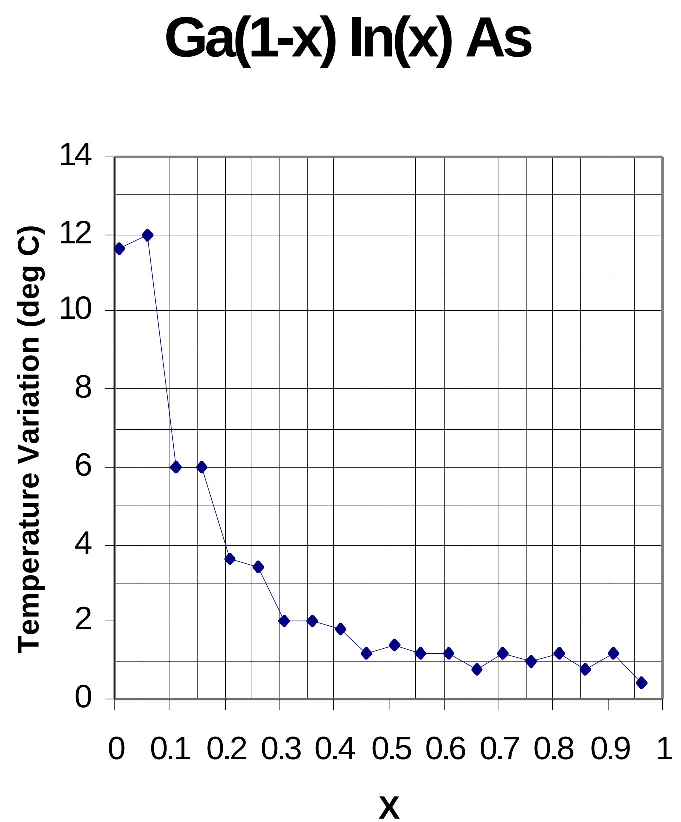


In-situ composition control is easier to implement and has produced highest quality ternary crystals

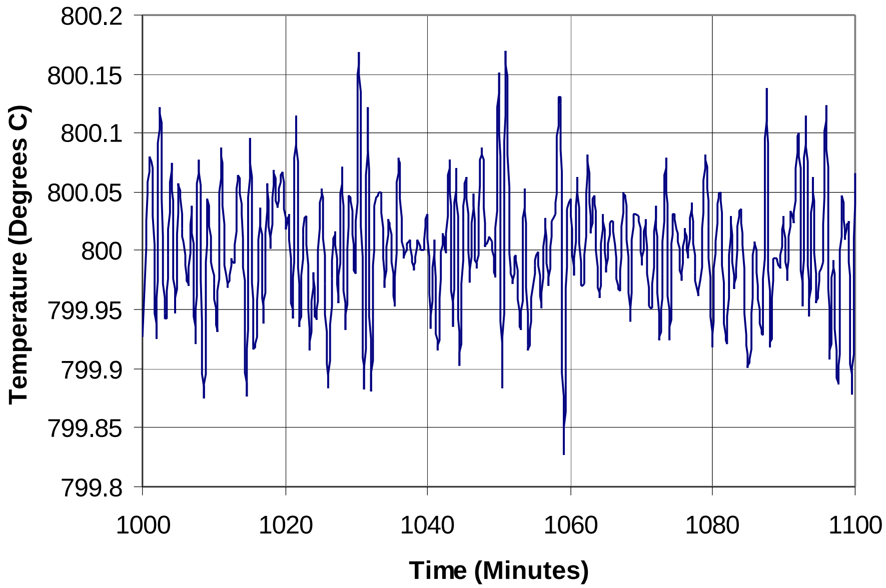
J. Crystal Growth **205**, 270 (1999) J. Crystal Growth **208**, 171 (2000) J. Crystal Growth **217**, 360 (2000)

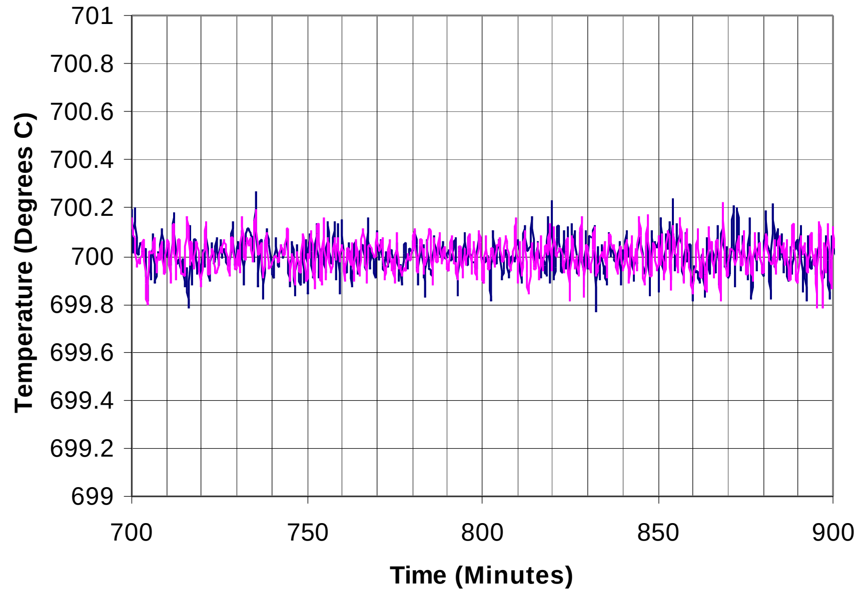
Temperature Stability Requirements for Homogeneous Ternary Growth





Temperature Stability of a Specially Designed Crystal Growth System (for alloy growth)





Temperature Fluctuations less than 0.2 ^{o}C

III-V Ternary Substrate Technology

- Well Established Technology
  - $Ga_{1-x}In_xSb$ (x = 0 to 0.45)
  - $Ga_{1-x}In_xAs$ (x = 0 to 0.35, 0.75 to 100)
- Under Development
  - $Al_{1-x}In_xSb$ (x = 0 to 0.4) for semi-insulating antimonide substrates

Engineering Phase Formation Thermo-Chemistry for Quaternary Alloys

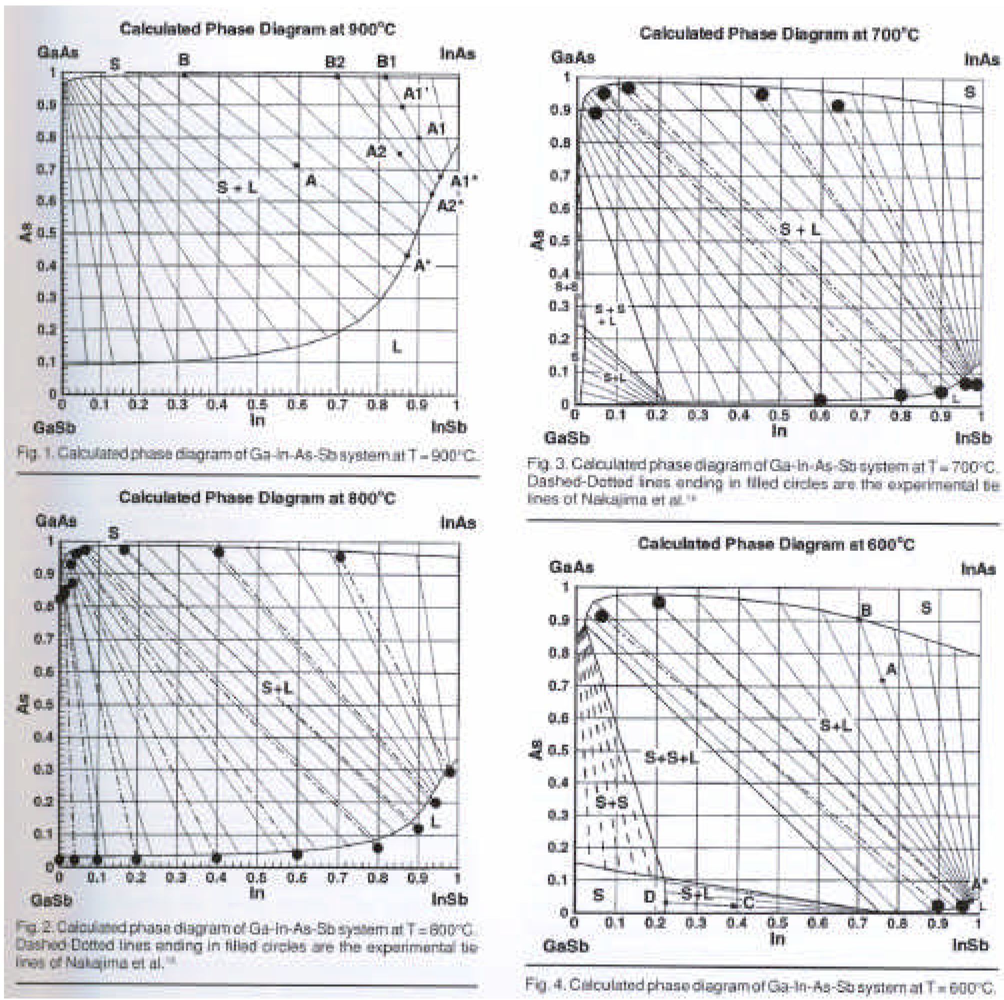


Fig. 1. Calculated phase diagram of Ga-In-As-Sb system at T = 900°C.

Fig. 2. Calculated phase diagram of Ga-In-As-Sb system at T = 800°C. Dashed-Dotted lines ending in filled circles are the experimental tie lines of Nakajima et al.

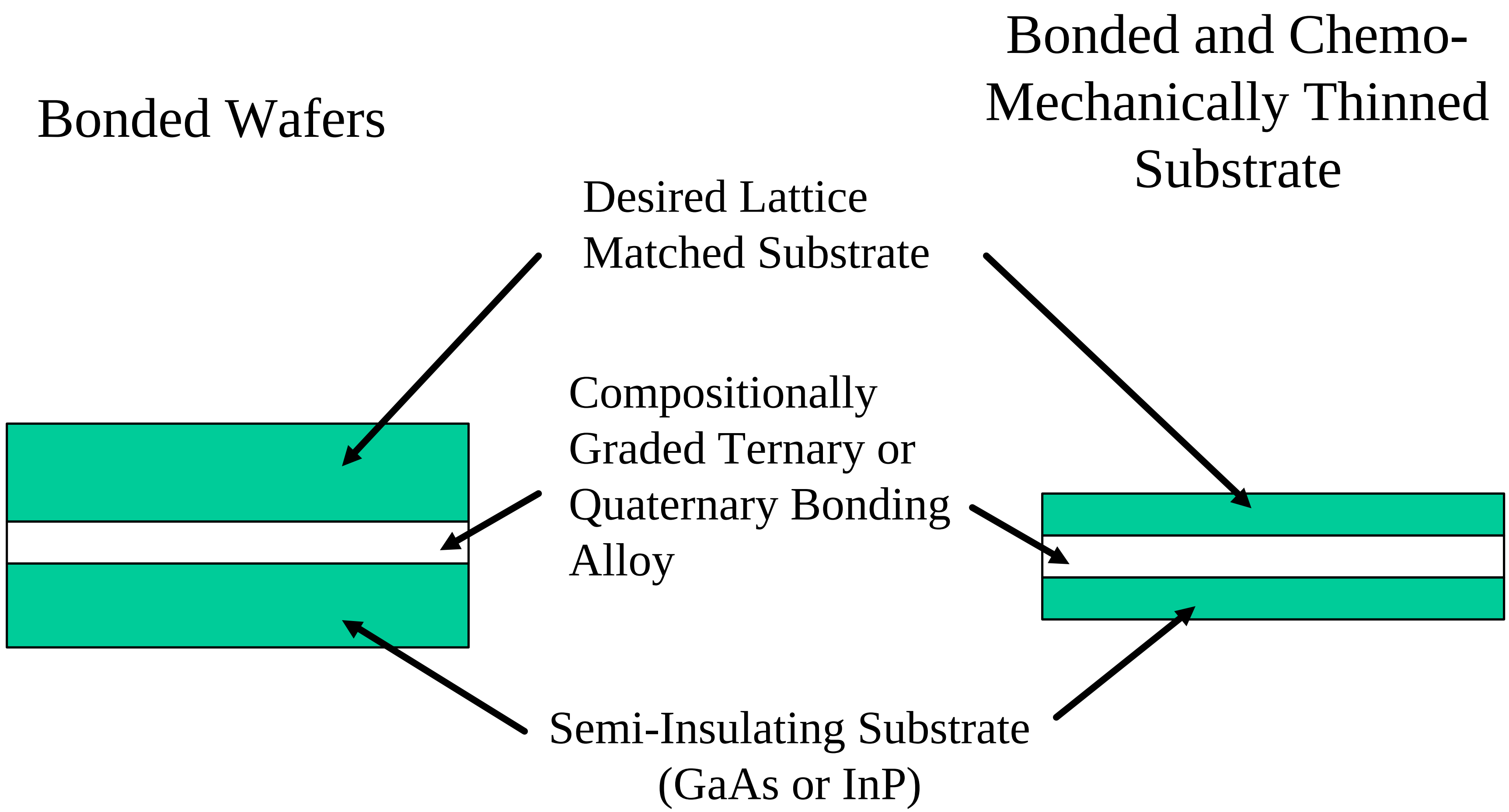
Fig. 3. Calculated phase diagram of Ga-In-As-Sb system at T = 700°C. Dashed-Dotted lines ending in filled circles are the experimental tie lines of Nakajima et al.

Fig. 4. Calculated phase diagram of Ga-In-As-Sb system at T = 600°C.

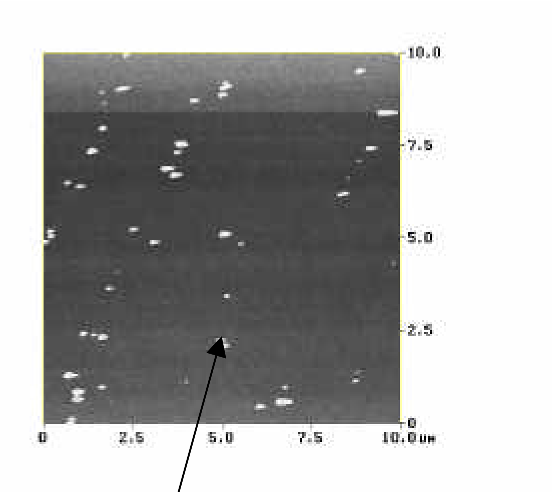
Phase formation and their composition is dependent on the sequence in which binary alloys are mixed

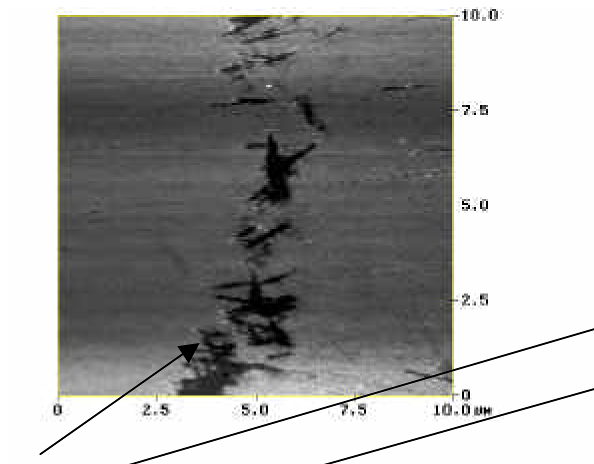
J. Elec. Mater. **29**, 956 (2000)

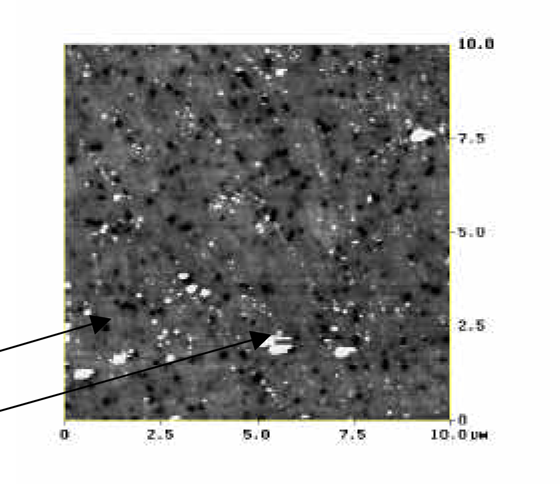
Alloy Bonding and Engineered Substrates



Surface Structures of GaSb Commercial Substrates (AFM Images)

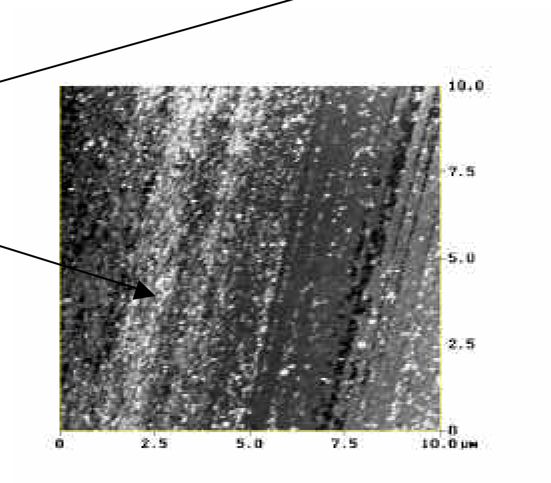


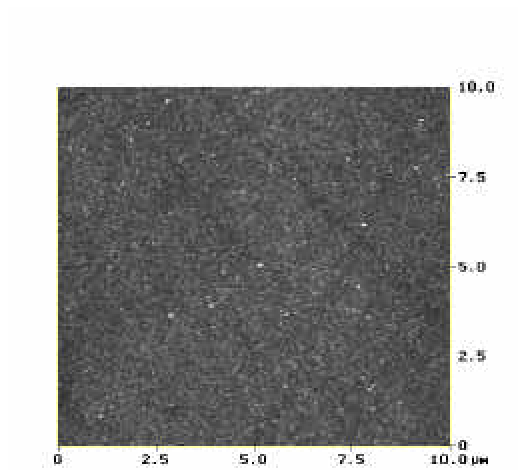




Micro-Cracks

Contamination from Slurry and Abraded Particles





RMS Roughness: 0.5 nm

Ultra-clean and atomically smooth surface

Summary

- Ternary Crystal Growth: More Science, Less Art
  - Reliable substrate technology has been developed for GaInSb and GaInAs: mass production yet to happen

- Quaternary Alloy Growth: “Sequential” and “Irreversible” Chemistry
  - Enables interesting possibilities such as hetero-bonding and epitaxy by alloying (apart from bulk quaternary substrates)

- Reliable chemo-mechanical polishing slurry for antimonides is not yet available. Chemical polishing results in better surfaces.